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PATENT

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SILICON MICROPHONE

DESCRIPTION

CROSS-REFERENCE TO RELATED APPLICATIONS:

Not applicable.

FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT:

Not applicable.

TECHNICAL FIELD:

The present invention relates to silicon microphones, and more particularly, to a silicon microphone having a diaphragm with reduced residual stress.

BACKGROUND OF THE INVENTION:

Micro-electromechanical systems (MEMS) technology allows the manufacture of small (microns to hundreds of micron) electromechanical components using the precision manufacturing techniques of microelectronics. The term often used to describe MEMS manufacturing process is *micromachining*. Prime examples of MEMS devices on the market include pressure sensors and accelerometers. See L. Sprangler and C.J. Kemp, ISAAC-integrated silicon automotive accelerometer, in Tech. Dig. 8th Int. Conf. On Solid-State Sensors and Actuators (Transducers '95), Stockholm, June 1995, pp. 585-588. See also W.S.

Czarnocki and J.P. Schuster. 1995. "Robust, Modular, Integrated Pressure Sensor," Proc 7th Intl Cong on Sensors, Nuremberg, Germany.

These devices typically consist of thin membranes and beams micromachined from films that are deposited or laminated on a substrate or, etched from the substrate itself. These micro-machined films ultimately serve as the mechanical structure and/or electrical connection. In the case where the film is deposited or laminated, a sacrificial layer is deposited first and then patterned using photolithography prior to film deposition or lamination. Patterning creates regions on the substrate that are free of the sacrificial layer and, thus the film can be deposited directly onto the substrate, i.e. anchored to the substrate. After the film has been micro-machined to a desired structure, the portion of the structure that is not anchored to the substrate is physically separated or disconnected from the substrate by removing the sacrificial layer underneath the micromachined structure.

One major difficulty often encountered in micromachining is the control of film stress. Film stress is the residual stress that is present in the film after formation. For the case of tensile film stress, the resulting micromachined structure will also be in tensile stress unless the micromachined structure is designed to strain and relieve the stress. Micro-machined cantilevers are a typical example of a structure that can relieve the residual stress.

For a MEMS microphone (condenser microphone), the part of the micromachined structure that actuates with an acoustic signal is the diaphragm. Stress on the diaphragm has a direct effect on the sensitivity of the microphone. Tensile stress severely decreases the mechanical compliance of a microphone diaphragm. The following idealized formula shows that decreasing the mechanical compliance decreases the sensitivity of a capacitor microphone:

$$Sens = \frac{C_{MS} SE}{x_0}$$

Here, C_{MS} is the mechanical compliance in meters per Newton; S is the area; E is the bias; x_0 is the distance between the microphone diaphragm and back plate; and Sens is the open circuit sensitivity of the microphone. It is clear, that in order to fabricate MEMS microphones whose sensitivity is minimally affected by the film stress, the diaphragm must be designed such that film stress minimally affects its mechanical compliance. One must

keep in mind that the diaphragm is fabricated from the very film which holds the residual stress.

One method of minimizing the effect of film stress is the free plate scheme. See Loeppert et al., *Miniature Silicon Condenser Microphone*, US Patent No. 5,490,220 and PCT application 01/25184, filed August 10, 2001 (claiming priority from U.S. Serial No. 09/637,401 and 09/910,110). In this method, the diaphragm is largely free with the exception of a narrow arm or arms. The function of the narrow arm is simply to provide an electrical connection to the diaphragm. This way the mechanically free diaphragm is allowed to strain and release the residual stress. Since the diaphragm is not rigidly attached to the substrate, it is necessary to mechanically confine the diaphragm on the substrate to prevent the diaphragm from detaching completely while handling. For the free plate design, the diaphragm hovers over an acoustic port that has been etched into the substrate (the substrate opening, which serves as the acoustic port, is smaller than the diaphragm diameter). In the free plate design, the back plate covers the diaphragm and provides the necessary confinement. Thus the diaphragm is confined by the substrate and the back plate located on either side of the diaphragm.

Implementing a microphone diaphragm design such as the free plate design is possible by using a fabrication process that is capable of depositing many conformal layers of thin film (See the above referenced PCT application).

In some microphone implementations, it is desirable to place the backplate between the diaphragm and the substrate. In other devices, there may not be a backplate at all. In these situations, there is insufficient constraints to keep the free plate diaphragm from being pulled away from the substrate and being damaged during processing or when handling a completed device. This invention describes a means to protect the diaphragm by constraining its out of plane travel yet which will strain to relieve in-plane stresses.

SUMMARY OF THE INVENTION:

In order to simplify the fabrication process it is necessary to combine the functionality of some of the mechanical structures. According to the invention, a diaphragm anchoring scheme is provided which renders the diaphragm essentially free, i.e., the film stress is

relieved and yet, the entire diaphragm is anchored in place on the substrate. This diaphragm design can be used for fabricating MEMS microphones with characteristic acoustic sensitivity that is relatively insensitive to the (diaphragm) residual film stress. In this design, the insensitivity of the diaphragm's compliance to residual film stress is achieved through the special anchoring scheme. Since the diaphragm is physically anchored or attached to the support substrate, no additional structure is required to contain the diaphragm. Hence the fabrication method is simpler than the free plate design described in the previous section.

Thus it is an object of the invention to provide a transducer.

In accordance with the invention, the transducer comprises a substrate forming a support structure and having an opening. The substrate can be formed of a conductive material or of a semi-conductor material, such as silicon, provided the substrate has an appropriately insulating film layer. Alternatively, the substrate can be formed of a wholly electrically insulating material. A thin-film structure forming a diaphragm responsive to fluid-transmitted acoustic pressure is disposed over the opening. The transducer further includes a plurality of supports and means for connecting the periphery of the diaphragm to the supports. The connecting means strains to permit the diaphragm to move to relieve film stress in the diaphragm. The transducer still further includes a plurality of stop bumps disposed between the substrate and the diaphragm. The stop bumps determine the separation of the diaphragm from the substrate when the transducer is biased.

It is contemplated that the transducer is a microphone.

It is further contemplated that the stop bumps are fabricated either from an insulating material or from a conductive material having an outer layer of insulating material.

It is still further contemplated that each of the stop bumps is anchored to the substrate and not to the diaphragm, or each of the stop bumps is anchored to the diaphragm and not to the substrate.

It is yet further contemplated that the connecting means comprises a plurality of arms extending generally tangentially outwardly from the diaphragm edge.

It is still further contemplated that the transducer includes a back plate, that the back plate is smaller than the diaphragm and the center of the back plate is aligned with the center of the diaphragm to minimize parasitic capacitance.

BRIEF DESCRIPTION OF THE DRAWINGS:

Other objects, features and advantages will occur to those skilled in the art from the following description and the accompanying drawings, in which:

FIG. 1 is a cutaway perspective view of a transducer according to the invention;

FIG. 2 is a top, bottom and side view of a diaphragm for the transducer of FIG. 1; and

FIG. 3 is a top view of the transducer of FIG. 1.

DETAILED DESCRIPTION OF THE INVENTION:

While this invention is susceptible of embodiment in many different forms, there is shown in the drawings and will herein be described in detail a preferred embodiment of the invention with the understanding that the present disclosure is to be considered as an exemplification of the principles of the invention and is not intended to limit the broad aspect of the invention to the embodiment illustrated.

A solid-state transducer **10** according to the invention is illustrated in FIG. 1. In the present description, the transducer **10** is shown as a condenser microphone. However, the transducer could be other devices, such as a pressure sensor or an accelerometer. The transducer **10** comprises a semi-conductor substrate **12** forming a support structure and having an opening **12a**. The transducer **10** further includes a thin-film structure forming a diaphragm **14** responsive to fluid-transmitted acoustic pressure. The diaphragm **14** is disposed over the opening **12a**. The diaphragm **14** includes a plurality of tangentially extending arms **14a**. A back plate **16** is attached to the substrate **12**, which has been coated with an insulating material. The back plate **16** may be formed of the same silicon as the substrate **12.**

The transducer **10** further includes a plurality of semi-conductor supports **18** coupling each of the arms **14a** to the substrate **12.** A plurality of stop bumps **20** are disposed between the substrate **12** and the diaphragm **14.** The stop bumps **20** determine the separation of the diaphragm **14** from the substrate **12**, and hence the backplate 16, when the transducer **12** is biased. A back volume **24** can be located underneath the back plate **16** and may be defined by using the substrate opening **12a** to cover an open-ended cavity.

Three different views of the diaphragm **14** are illustrated in FIG. 2. The top view shows the diaphragm **14** anchored to the substrate **12** via the spiral arms **14a**. When the entire structure is released from the substrate **12** (with the exception of the anchor points), the spiral arms **14a** strain and thus relieve the build-in film stress in the diaphragm **14.** The entire diaphragm **14**, including the spiral arms **14a**, is a conductor which may be doped silicon, poly-silicon, or silicon-germanium.

The bottom view of FIG. 2 shows the stop bumps **20.** The stop bumps **20** are fabricated from an insulator. Alternatively, the stop bumps **20** are a conductor with an outer insulating layer.

In the preferred embodiment, the transducer **10** has twenty of the stop bumps **20.** Each of the stop bumps **20** is anchored to the substrate **12** and is not attached to the diaphragm **14** located just above the bumps. Having the stop bumps **20** not attached to the diaphragm **14** allows the diaphragm **14** to move when relieving the film stress. The stop bumps **20** serve as controlled boundary condition when the diaphragm **14** is responding to sound waves and when the diaphragm **14** is biased. Specifically, the stop bumps provide a simply supported boundary to the stress-relieved diaphragm **14** and also determine the nominal distance between the diaphragm **14** and the back plate **16** when the transducer **10** is biased. The distance between the top of the bumps **20** and the bottom of the diaphragm **14** when the diaphragm **14** is not biased, as well as the diameter of the bumps **20**, depend on the available fabrication technology.

The acoustic path, or leak, defined by a path from the ambient to the back volume which is surrounded by the bumps **20**, the diaphragm **14** and the substrate **12**, is necessary in order to accommodate varying ambient pressure. In order to control the acoustic resistance of this leak, additional bumps **20** may be placed underneath the diaphragm **14** or at the perimeter of the diaphragm **14** to restrict the acoustic leak from ambient to the back volume **24.** Alternatively, the gap set by the height of the bumps **20** can be adjusted, or the overlap of the diaphragm **14** and the substrate hole can be changed.

The side view on the bottom of FIG. 2 shows the location of the back plate **16.** The back plate **16** is a conductor. The back plate **16** may be perforated with holes or slots to provide desired damping of the movement of the diaphragm **14** when actuating and to lower

the acoustic noise. The back plate **16** must be much thicker or stiffer than the diaphragm **14.** In addition, the back plate **16** must be smaller than the diaphragm **14**, and the center of the back plate **16** must be aligned to the center of the diaphragm **14** in order to minimize parasitic capacitance.

Referring again to FIG. 1, the substrate **12** is shown having a tapered hole, or acoustic port. This is characteristic of silicon anisotropic etching and is commonly found in bulk micro-machined silicon structures. The thickness of the diaphragm **14** is exaggerated for visual clarity. As stated previously, the back plate must be much thicker (or stiffer) than the diaphragm.

FIG. 1 shows the diaphragm **14** anchored to the substrate **12** at the end of the spiral arms **14a**. The substrate **12** is coated with a layer of insulator to avoid electrical shorting of the back plate **16** and the diaphragm **14.** An electrical connection (not shown) is provided to both the back plate **16** and the diaphragm **14.** The electrical connection may be achieved trivially using conducting runners. Therefore, electrical connections are not shown in the FIGS..

For operation as a microphone, the transducer **10**, as shown in FIG. 1, is placed over a hole in a cavity with a known back volume. The diaphragm **14** is then electrically biased against the back plate **16.** The spiral arms **14a**, which anchor the diaphragm **14**, allow the diaphragm **14** to be nearly stress free before biasing. Upon biasing, the diaphragm **14** rests against the bumps **20.** On exposure of the diaphragm **14** to sound waves, actuation of the diaphragm **14** occurs, and the electrical signal generated by the moving diaphragm center is detected using a high impedance amplifier. As stated above, the back plate **16** is stiffer than the diaphragm **14.** Actuating the diaphragm **14** and the stationary back plate **16** forms a variable capacitor, where the variance of the capacitance is induced by the acoustic signal.

FIG. 3 shows the geometrical dimensions of a version of the microphone that incorporated the diaphragm design. This is a top view of the diaphragm **14.** The diaphragm **14** has an effective diameter **30** of 550 μm. The diaphragm **14**, including the tangential arms **14a**, has a total diameter **32** of 710μm. Each tangential arm **14a** has a width **34** of 16μm., and a radius of curvature **36** of 150μm. The back plate **16** has a diameter **38** of 400μm, and the distance between the diaphragm **14** and the back plate **16** is 4μm. The outline of the back

plate **16** located underneath the diaphragm **14** is also shown in FIG. 3. As stated earlier, the diameter of the back plate **16** is smaller than the diameter of the diaphragm **14** to minimize the parasitic capacitance.

While the specific embodiments have been illustrated and described, numerous modifications come to mind without significantly departing from the spirit of the invention and the scope of protection is only limited by the scope of the accompanying Claims.